Greenhouse gas emissions – timing matters!

Key findings

- Using Global Warming Potential (GWP) to establish CO_2 equivalence doesn't capture temporal variation
- Delaying emissions affects their climate impacts
- Different greenhouse gases have different impacts that vary relative to each other with time
- Temperature effects and heating effects are not always the same
- Simple spreadsheet tool available to assess temporal impacts of emissions

Introduction

Greenhouse gases (GHGs) cause climate change. However, the actual climate-change effects occur after the emissions that cause them and the variation with time of these effects is important in understanding their potential impact. The principal GHG is carbon dioxide (CO_2) but there are many others such as methane (CH_4) and nitrous oxide (N_2O). For simplicity, the effects of these GHGs are often combined in terms of CO_2-equivalent mass (CO_2e). However, **what does "equivalent" really mean?** And, given that the various GHGs have different potencies and lifetimes, **does this "equivalence" mask anything?** To complicate matters further, while some systems cause emissions at a single point in time, others (such as bioenergy) cause various emissions and absorptions of GHGs over a period of many years. Their GHG emissions might balance out overall, but **what effect does their timing have on their impact?**

In this note, we will clarify these issues and look at a couple of case studies involving bioenergy, based on recently published work. While CO_2 equivalence is a sensible metric for lots of applications, in some cases it doesn't tell the full story.

The timing of GHG emissions, and what those emissions are, matters!

Dynamics of impacts from GHGs – understanding CO_2 equivalence

To understand "CO_2 equivalence", we must look briefly at how the effects of GHGs vary. This is mainly determined by their potency (the ability of a 1kg mass of that gas in the atmosphere to trap heat) and the way that the mass of that gas in the atmosphere decreases with time after it is first released (due to either decay or reabsorption).

This is shown in Figure 1. In Figure 1a (top left), we see that less than half of a mass of CO_2 released to the atmosphere remains after 50 years, but the rate of reduction then flattens out. On the other hand, a mass of methane (CH_4) is halved after only eight years before almost disappearing after 40 years. However, because methane is so much more potent, the "instantaneous radiative forcing" due to the pulse emission of 1kg of CH_4 (effectively, the "heating power per area of land", measured in Watts per square metre) is initially much greater. After around 70 years, the reduced quantity of CH_4 remaining in the atmosphere means that they crossover and the heating power of the remaining CO_2 is greater.

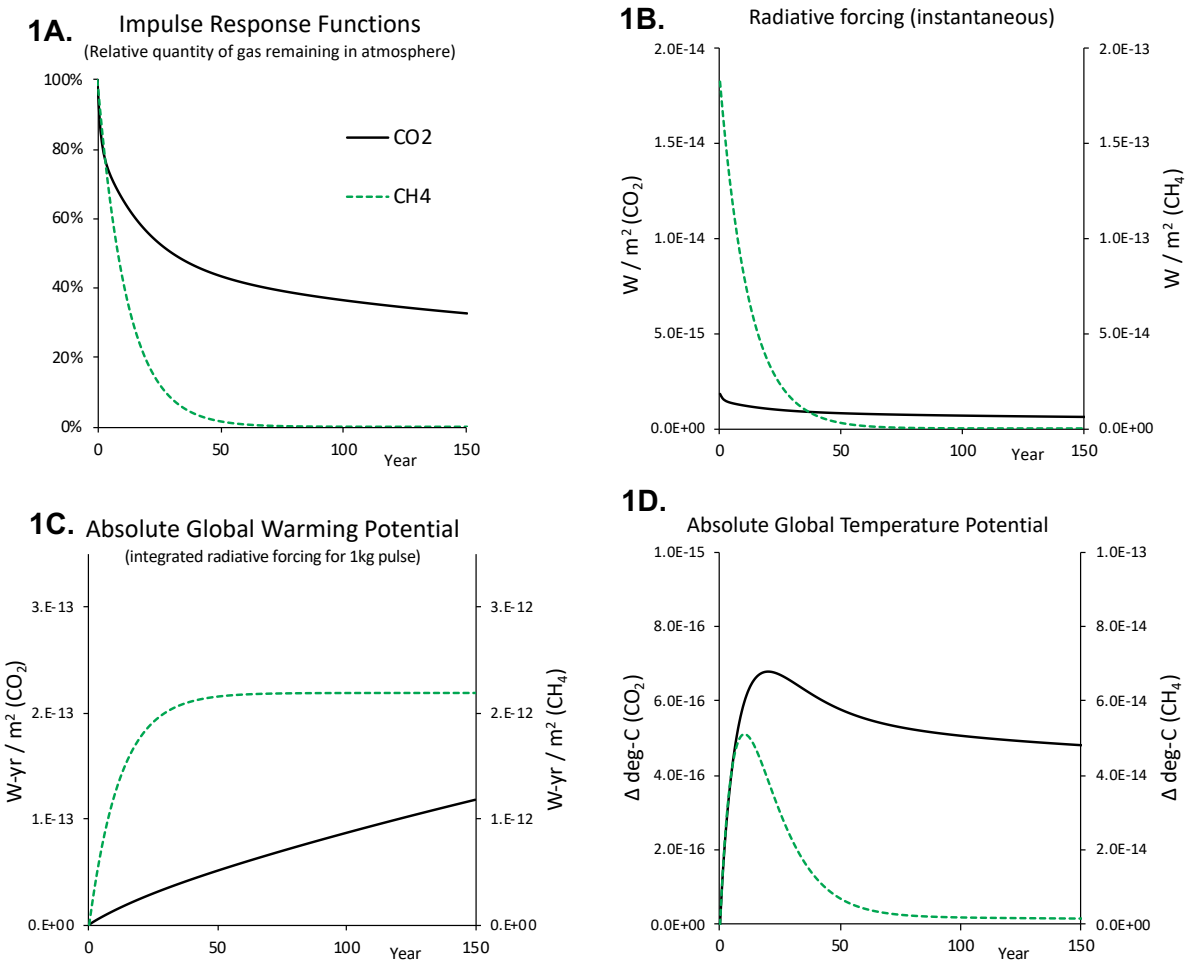

Figure 1: Warming effects of 1kg-pulse emissions of CO_2 and CH_4

Rather than considering just the heating power at a point in time though, perhaps we are more interested in the total (gross) additional heat captured up to that point. This is the integrated radiative forcing (the area under the plots in Figure 1b, shown in Figure 1c) and is the basis underpinning the **Global Warming Potential (GWP)** metric. Because a significant proportion of CO_2 remains in the atmosphere, the integrated radiative forcing (the gross extra heat) due to an initial release of CO_2 continues to increase (as more and more heat is captured). However, the integrated radiative forcing due to an initial release of methane stops increasing substantially after about 40 years because almost all of the gas has decayed away.

While some impacts relate to heating, others might relate more to the temperature increase that this contributes to. A simplified indication of the atmospheric temperature response (e.g. in degrees Celsius) due to this gross additional heat input can be provided by an idealised climate response model (Figure 1d). This is the basis underpinning the **Global Temperature Potential (GTP)** metric. The peak temperature response due to a release of CO_2 occurs after about 20 years and then remains balanced at about 75% of the peak for a long period. The peak temperature response due to methane occurs after about 10 years but then (over the following 40 years) reduces to a fraction of this as no methane (and therefore no additional heating) is available to maintain the temperature.

CO_2 equivalence is based on the idea that after a defined period of time (typically 100 years), the integrated radiative forcing (basis for GWP) or temperature effect (basis for GTP) due to an initial release of 1kg of that GHG (e.g. methane) will be the same as the effect due to an initial release of a mass of CO_2. **This mass is the "CO_2-equivalent mass".**

The combined effect of GHGs - what does "equivalence" mask?

It might now be clear that the CO_2-equivalent mass of a GHG emission depends upon whether we are considering an equivalent heating effect or an equivalent temperature effect. Additionally, because the effects vary at different rates, the **CO_2 equivalence also depends upon when the effect is considered (the "time horizon").**

We can illustrate this with a case study. In this case, we're interested in comparing the climate change impacts of two bioenergy options. In the first option, woodchips from forest waste are used. In the second option, a technology called Anaerobic Digestion (AD) is used to produce methane from slurry. In these examples, the AD option prevents methane from being released to the atmosphere but causes more CO_2 to be released. The details of the options are provided in the original study[1] but here we're more interested in the differences they illustrate than the actual systems.

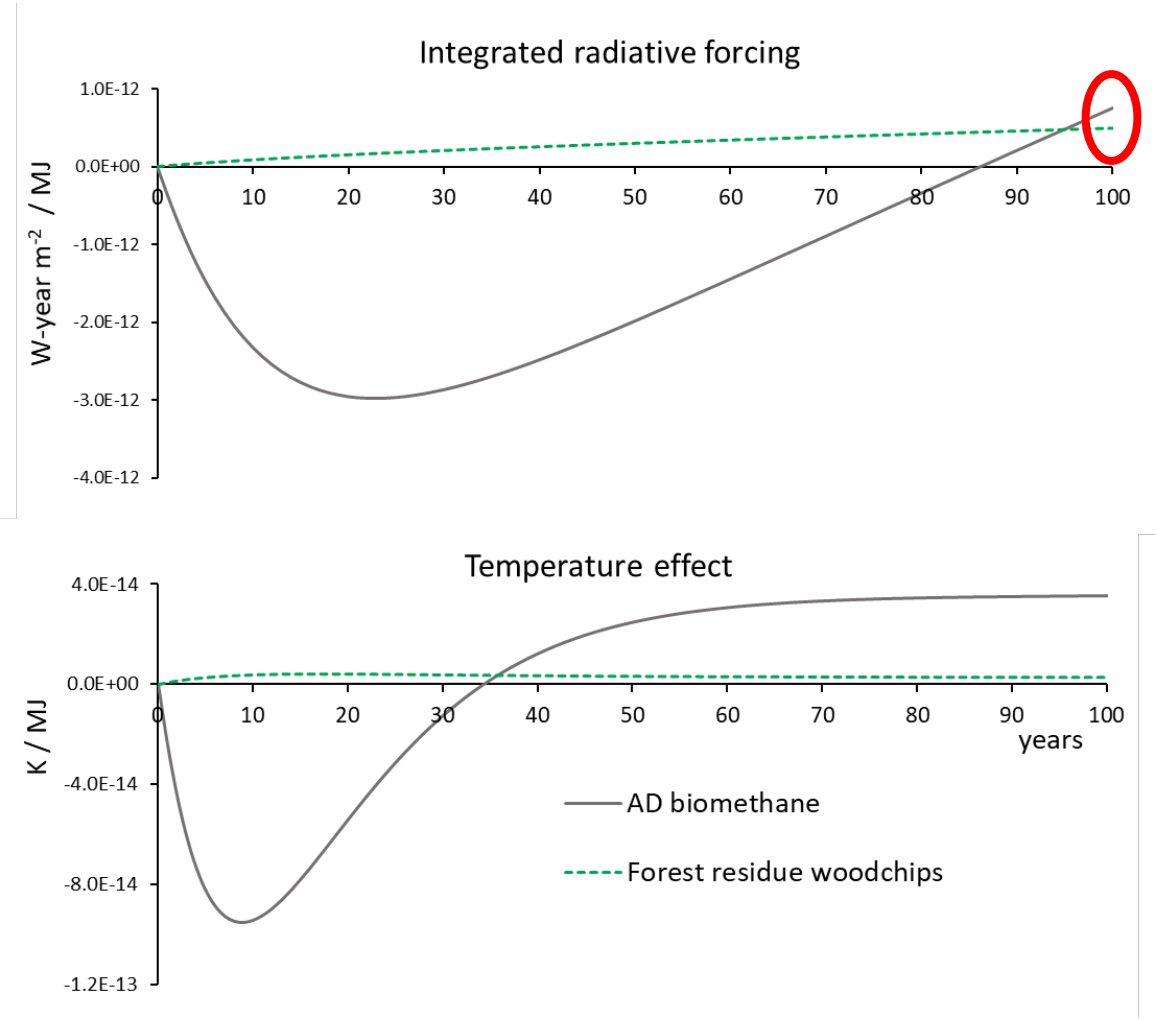

Figure 2: Climate change effects of examples from case study 1 (AD and forest residues)

Figure 2 compares how the climate-change impacts of these two options varies with time after the bioenergy is used, due to the effects explained above. After 100 years, both options result in a similar integrated radiative forcing effect (the points on the plots circled in red). That is, they would have a similar "CO_2e" result, based on the GWP_{100} (GWP with 100-year time horizon) metric. However, for any time horizon that is less than 85 years after the operation of the systems, the anaerobic digestion system has a negative heating effect due to the greater influence of the avoided CH_4 emissions.

The temperature impact of the systems is also complex. Both systems cause a consistent temperature increase for the period later than 60 years after they're operated. However, while the temperature increase due to the AD system in this later period is far greater, it actually causes a temperature *decrease* until 35 years after it is operated!

Depending upon the impacts that we're concerned about and when we're concerned about them occurring, either option might be preferable. While a single metric like CO_2 equivalence can be representative for some cases, there are clearly cases when **CO_2 equivalence simply can't communicate everything that we'd like it to.**

Dynamics of emissions – what effect does their timing have on their impact?

Many real systems do not just have a pulse emission of GHG at one point in time but rather a series of emissions and absorptions over an extended period. A good example of this is bioenergy in which CO_2 might be released from biogenic and non-biogenic sources, and also reabsorbed by biological activity, over an extended period. Given the dynamics we see above, it is worth considering how this might affect the overall climate-change impacts of these systems.

To explore this, we're using a forestry case study in which short-rotation eucalyptus was used to provide energy[2]. The study modelled periodic forest management activity, CO_2 release due to burning the biomass and CO_2 absorption due to regrowth. While individual forest stands will experience significant year-on-year changes, the sustainable rotational forestry practice modelled in the case study smooths these out.

The cumulative net GHG emissions from the case study are compared to their climate-change effects in Figure 3. The cumulative GHG net emissions follow a curve that is caused by the dynamics of the forestry activities and practices in this particular example. These cumulative net emissions are the ones that might typically be reported as the GHG effect of the forestry.

However, we can see that the actual increase in atmospheric GHGs that these emissions result in is far less; much of the emissions are reabsorbed by other systems. In this case, the integrative radiative forcing effect is similarly lower than the cumulative emissions (as the GHGs emitted later haven't had as much time to have an effect). On the other hand, the temperature effect is more varied but ends up higher than the cumulative net emissions (as the later emissions have more influence on the temperature response).

These differences follow some patterns but are determined by the dynamics of the underlying emissions and absorptions. It is hard to accurately assess the impacts without knowing this; the **cumulative net emissions on their own will not always reflect the impacts**.

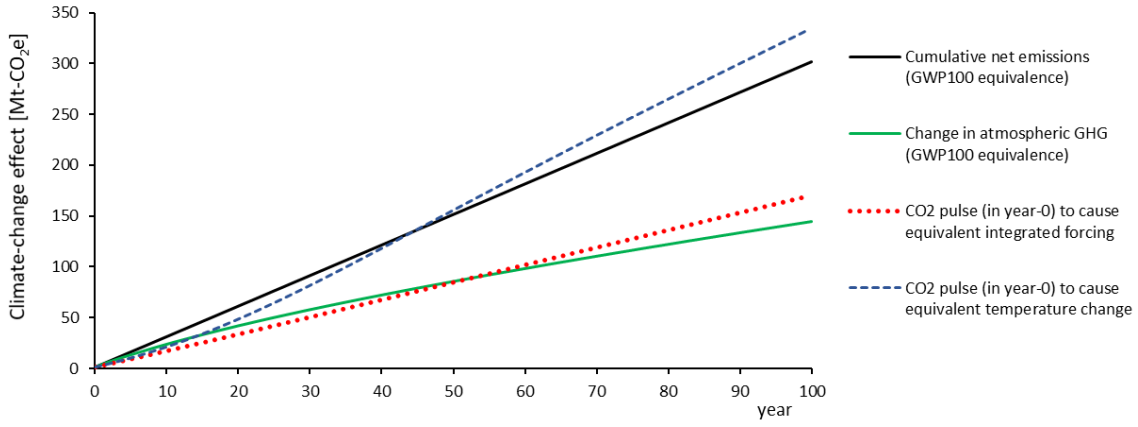

Figure 3: Climate-change effects of forestry case study vary with time - Alternative measures of CO_2 equivalence

Conclusions

The climate-change impacts of GHGs vary with time in a way that depends upon the dynamics of their emissions and upon their individual characteristics. Single figure metrics such as CO_2-equivalence based on GWP_{100} can be very helpful to compare systems but can't always communicate the full picture.

To avoid giving potentially misleading results, we suggest that researchers and others presenting GHG emissions should first check whether a single figure metric adequately communicates any other dynamics (we have produced a simple spreadsheet tool to facilitate this[3]) and then decide whether they should supply additional information to communicate the relevant impacts.

Notes

[1] Green, R., 2019. Optimising bioenergy use in district heating systems in the EU. Bath: University of Bath. https://researchportal.bath.ac.uk/en/studentTheses/optimising-bioenergy-use-in-district-heating-systems-in-the-eu

[2] Röder, Mirjam, et al. "Understanding the Timing and Variation of Greenhouse Gas Emissions of Forest Bioenergy Systems." *Biomass and Bioenergy*, 2019, doi.org/10.1016/j.biombioe.2018.12.019.

[3] Cooper, S., in press. *Temporal Climate Impacts.* Bath: University of Bath Research Data Archive. doi.org/10.15125/BATH-00787

Authors

Sam Cooper, Rowan Green, Laura Hattam, Mirjam Röder, Andrew Welfle, Marcelle McManus

Contact: sjgcooper@bath.edu

Supergen Bioenergy

www.supergen-bioenergy.net

The Supergen Bioenergy Hub works with academia, industry, government and societal stakeholders to develop sustainable bioenergy systems that support the UK's transition to an affordable, resilient, low-carbon energy future.

The hub is funded jointly by the Engineering and Physical Sciences Research Council (EPSRC) and the Biotechnology and Biological Sciences Research Council (BBSRC) and is part of the wider Supergen Programme.
Grant: EP/S000771/1

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